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ABSTRACT

A study investigated the size of the perceptual span within which adults use visual information to distinguish among letters as they read. The eye movements of fifteen college students were monitored as they read passages from a cathode-ray tube. On occasional fixations, letters in specified visual regions were replaced by other letters. The effects of this manipulation were observed on subjects' eye movement patterns. Results showed that erroneous letters lying four or more letter positions to the left of the fixated letter, or eight or more to the right, had no discernible effect on reading. In addition, there was no evidence to indicate that prior research in which letters were replaced on every fixation had underestimated the size of the perceptual span. The fact that the study yielded a smaller estimate of the perceptual span and showed smaller effects from letter replacement than have previous studies can be explained by methodological differences in the aspect of the text stimulus being studied. (Materials used in the study are appended.) (Author/FL)

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CENTER FOR THE STUDY OF READING

Technical Report No. 272

PERCEPTUAL SPAN FOR LETTER DISTINCTIONS DURING READING

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Abstract

This study investigated the size of the visual region within which adults use visual information to distinguish among letters as they read. Fifteen college students read passages from a cathode-ray tube as their eye movements were monitored. On occasional fixations, letters in specified visual regions were replaced by other letters. The effects of this manipulation were observed on their eye movement patterns. Erroneous letters lying four or more letter positions to the left of the fixated letter, or eight or more to the right, had no discernible effect on reading. There was no evidence to indicate that prior research in which letters were replaced on every fixation had underestimated the size of the perceptual span. The fact that the present study yielded a smaller estimate of the perceptual span and showed smaller effects from letter replacement than have previous studies is explained by methodological differences in the aspect of the text stimulus being studied.

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Perceptual Span for Letter Distinctions During Reading

McConkie and Rayner (1975) introduced a technique for investigating the size of the visual region within which readers use stimulus information during fixations as they read. Previous techniques which had been used to estimate the size of this "perceptual span" had either engaged the reader is tasks other than normal reading, such as identifying words and letters presented in isolation (Bouma, 1971) or for very brief periods (Cattell, 1885), or had been based on questionable assumptions about the relationship between saccade length and the size of the perceptual span (Taylor, 1965). McConkie and Rayner developed a computer-based eye movement contingent display control system which made it possible to make changes in the text display while a person was reading, contingent on the reader's eye behavior. With this capability, it was possible to selectively replace letters in certain visual regions on each fixation (e.g., all letters more than 10 letters to the right of the letter directly fixated[1]) and find out whether having inadequate or incorrect information in this region reduced reading efficiency. It was assumed that if this manipulation affected the reading process, as indicated by changes occurring in the eye movement pattern, then there would be evidence that visual information of the type manipulated was normally being used from that region during reading. A number of studies have now been carried cut using this technique to explore aspects of the perceptual span (McConkie & Rayner, 1976; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981;

Rayner, Well, & Pollatsek, 1980; Rayner, Well, Pollatsek, & Bertera, 1982).

A potential problem with this technique was pointed out by O'Regan (1980). He raised the possibility that with errors occurring consistently in a certain visual region on each fixation, readers may come to restrict their attention to a narrower area in order to avoid attending to the region containing inappropriate information. If this restriction were occurring, then these studies would consistently underestimate the size of the region from which readers obtain visual information from the text during fixations.

The validity of this criticism can be assessed by using the same technique while making the experimental manipulations only occasionally during reading. Thus, on most fixations the entire line of text would be normal, so the reader would be less apt to learn to avoid attending to certain regions. The purpose of the study to be described here was to obtain data on the size of the perceptual span under such conditions, and to see whether it is indeed larger than that reported in earlier studies. A second purpose was to make a more precise measurement of the region within which adult readers obtain and use information concerning the letters of the text, as opposed to word length, word shape or other aspects of the text stimulus pattern. Finally, since in this study the changes in the text occurred only on occasional fixations, it is possible to determine whether the manipulation had its effect on the fixation on which the errors were present or only on later fixations,

thus contributing to our understanding of the degree of immediacy in the control of eye movements during reading (McConkie, 1983; Rayner & Pollatsek, 1981).

Method

Subjects

Fifteen college students who responded to a newspaper advertisement, who had normal uncorrected vision, who were native English speakers, and who did not have facial structures which made it difficult to monitor eye movements, served as subjects. These students had participated in other eye movement studies, and were accustomed to reading in the laboratory setting.

Apparatus

The text was displayed, one line at a time, on a computer-controlled Cathode-Ray Tube or CRT. This CRT is a Digital Equipment Corporation VT-11, with upper and lower case characters produced by a hardware character generator. The tube has a P-31 phosphor which decays to 1% of the original intensity in 500 microsec. This display is interfaced with a PDP-11/40 computer. Pressing a button called the next line of text onto the CRT, permitting subjects to read multi-line passages without difficulty. The line of text was refreshed every 3 msec and the entire line could be changed in the period of a single refresh cycle. The CRT was 48 cm. from the subjects' eyes, with three letter positions subtending one degree of visual angle.

Eye movements were monitored using a modified Biometrics Model SC limbus reflection eye movement monitor (Young & Sheena, 1975) which was also interfaced with the computer. The computer sampled the horizontal component of the eye position every msec. The computer program used in conducting the research was developed to produce changes in the line of text contingent on specific aspects of the reader's eye movement pattern. A more complete description of this system can be found in. McConkie, Zola, Wolverton, and Burns (1978)

Experimental Manipulations

On selected fixations during reading, letters in certain regions of the display, defined with respect to the reader's point of fixation, were replaced by other letters, thus providing erroneous text in specific retinal regions. These regions are referred to as letter replacement regions. In such a region, each letter was replaced by its most visually dissimilar letter from the same set, where letters were grouped into three sets: ascenders, descenders, and those which neither ascend above nor descend below other letters. Visual similarity was determined by norms collected earlier using the same equipment (McConkie, Blanchard, Zola, & Wolverton, November, 1982). Thus, replacement letters were as different from the original letters as possible, within the limitations of the set of English letters and without changing the external shape of the word. A 'letter replacement region' was determined by defining a boundary with respect to the reader's point of fixation. This boundary could lie to the left of the

letter which the computer indicated was directly fixated or to the right of it, a given number of character positions. If the boundary were to the left, then all letters to the left of this point were replaced by other letters in the manner described; if the boundary were to the right, then all letters to the right were replaced. The letter string in a replacement region typically contained no English words, and frequently violated English orthography, but preserved other aspects of the original text such as the general shapes of words, word lengths, and punctuation.

Eight letter replacement regions were selected for this study: Left-0 (all letters to the left of the fixated letter were replaced), Left-2 (all letters more than two to the left of the fixated letter were replaced), Left-4, and Left-80 (all letters more than 80 to the left were to be replaced; however, since text lines were never eighty characters long, this was a control condition in which no letters on the left were actually replaced), Right-6 (all letters more than 6 to the right of the fixated letter were replaced), Right-8, Right-10, and Right-80.

The actual replacement occurred very early in the fixation, as soon as the saccadic movement was completed (i.e., as soon as no further progress of the eyes was detected in a 4 msec. period). Since this criterion involved a 3 msec delay, and since the eye movement signal lags about 3 msec behind the eye's actual behavior, and since 3 msec is required to change a line on the CRT, the actual change occurred within

about 10 msec after the beginning of a fixation. When the following saccade was detected, the modified line of text was returned to its original form. Thus, the letter replacement occurred for only a selected single fixation.

The algorithm which made these display changes resulted in occasional errors of two types. First, there were instances where the saccade following a fixation on which erroneous letters were present was so short that the algorithm failed to identify when movement occurred, resulting in erroneous letters being present on the following fixation as well. This involved saccades of less than two character positions in length. These saccades were identified by a more accurate data analysis algorithm following reading, and such instances were eliminated from analysis. Second, blinks and other eye-lid movements sometimes were interpreted as a saccade by the on-line algorithm, causing text changes to occur when they were inappropriate. Again, these instances were later identified and excluded from the data set. Thus, the only fixations included in the data analysis were those on which the display changes occurred at the appropriate times, according to the above description.

Materials

Sixteen passages of expository text were selected from daily newspaper articles. Each passage was edited and formated to be 20 lines long, with up to 72 character positions per line. A variety of different types of questions were prepared, five for each passage, which

included multiple-choice, true-false, sentence completion, and short answer questions, mostly calling for retention of statements of fact in the passages.

Design

Eight letter replacement regions were used in this study, four to the left of the fixated letter and four to the right. In fact, on each critical fixation, there were two letter replacement regions, one to the left and one to the right. Thus, the design involved using all combinations of one left and one right region, for a total of 16 different combinations, or experimental conditions. The region of normal text on a given fixation could range from only seven character positions (Condition Left-0--Right-6) to the entire line (Condition Left-80--Right-80). Examples of how the line of text might have appeared on a fixation in which letter replacement occurred, under several different conditions, is shown in Figure 1.

Insert Figure 1 about here

No replacement occurred on the first or final two lines of each passage. On the remaining 16 lines the fixations following the 4th and 7th saccadic movements on the line were designated as critical fixations (i.e., those on which the replacement occurred). Both critical fixations on a line were assigned the same replacement condition. Across the 16 passages, the 16 middle lines of each passage were assigned to the 16 experimental conditions according to a Latin-square

design. Thus, the maximum number of fixations on which a given condition was implemented for a subject was 32 (twice on each of 16 lines).

With this design, a normal line of text was present on about 80% of the fixations made during reading. In addition, our experience suggested that several of the experimental conditions used had errors at visual regions where they would have no impact on reading. Thus, it was expected that subjects would only encounter the erroneous letters on a small fraction of the critical fixations which would not be enough to produce a change in the visual region attended during a fixation.

Procedure

Subjects read the passages silently as their eyes were being monitored. A bite bar and forehead rest were used to reduce head movement. Two warm-up passages were read at the beginning of each experimental session, similar to those used in the experiment, and with similar experimental manipulations being made, in order to familiarize the subjects with the task.

A calibration task described by McConkie (1981) was used before and after reading each passage in order to determine the amount of head movement that had occurred. After reading each passage, subjects took the retention test in written form. The test was immediately checked and the subjects were given feedback on their performance, with any wrong answers being discussed. This procedure was used to keep the

primary emphasis on reading the passages for meaning.

Subjects required two 1-hour sessions to complete the study.

Data

As the data were being collected, an on-line algorithm identified the beginning and end of each fixation and set a unique bit in the data word to indicate each of these events; it also set a bit to indicate when a display change was initiated (i.e., at the beginning or end of a fixation). This information was examined visually to ensure that the display changes were occurring appropriately. However, following the data collection the raw data were reanalyzed to identify beginnings and ends of fixations more precisely. The data reduction program identified a saccadic movement on the basis of a velocity threshold which was low enough to detect movements of 1/2 letter position. From this threshold point, it then proceeded to examine prior data values to find the beginning of the saccade (i.e., the point at which no forward movement was found in a 4-msec period with the end of that period being identified as the end of the prior fixation), and then proceeded to examine subsequent data values to find the end of the saccade, using the same threshold for its identification. The program also identified disturbances in the eye movement pattern which were not saccadic movements (e.g., blinks and squints).

A data matrix was created from all of the subjects' eye movement records which contained a row for each critical fixation. This row

contained information about the duration of that fixation and the one following, and the direction and length of the saccade following the critical fixation. Data were excluded from this matrix if any of the following were true: a blink or other eye movement disturbance occurred on the critical fixation or the saccade or fixation following; the saccade prior to the critical fixation was a regression; a small saccade followed the critical fixation during which the text was not returned to normal; or the calibration values obtained prior to and following the reading of the passage differed by more than an amount equivalent to two character positions indicating excessive head movement during reading.

Results

While it was theoretically possible for each subject to have a total of 32 critical fixations in each experimental condition, the actual number was reduced by the elimination of data as described above, and by the fact that occasionally subjects failed to make enough fixations to cause the second manipulation on a line to occur. Thus, the number of data values per condition for individual subjects ranged from 16 to 31, with an average of 26. Since frequency distributions of eye movement measures tend to be highly skewed, the data analyses were carried out by calculating a median for each subject for each dependent variable to be analyzed, and then entering these medians into an analysis of variance. These analyses included as fixed effects left boundary location (Left-0, -2, -4 and -80) and right boundary location (Right-6, -8, -10 and -80). Subjects were considered a random factor.

Since there were no significant interaction effects between left and right boundary location for any of the dependent variables studied, and since interactions with subjects were not testable, only the main effects will be discussed further. Three dependent variables will be discussed: the duration of the critical fixation (labeled fixation F0), the length of the following saccade (labelled saccade S1), and the duration of the following fixation (labelled fixation F1).

Duration of Fixation F0

The left boundary location was found to have a significant effect on the duration of fixation F0, $F(3,45) = 3.72$, $p < .05$, but the right boundary location did not, $F(3,45) = 1.23$, $p > .05$. These data are shown in Figure 2a.

Insert Figure 2 about here

Replacing all letters to the left of the directly fixated letter increased the median duration of the fixation by 9 msec., in comparison with the control condition (Condition Left-80), a difference not quite significant at the .05 level by Dunnett's test (Kirk, 1968). Replacing all letters more than 6 to the right had almost no effect on the duration of that fixation (i.e., there was a 4 msec decrease).

Length of Saccade S1

Length of forward S1 saccades showed a significant main effect due to left boundary location, $F(3,45) = 3.54$, $p < .05$, but not for right

boundary location, $F(3,45) = 1.57$, $p > .05$. Figure 2b presents these data. Replacing all letters to the left of the fixated letter reduced forward saccade length by 0.4 character position, as compared with the control condition Left-80, a difference that is not significant. Condition Right-6 showed a decreased saccade length of only 0.3 character positions as compared to the control Right-80.

Duration of Fixation F1

The left boundary location had a significant effect on the duration of fixation F1, that is, the fixation following the manipulation, $F(3,45) = 3.12$, $p < .05$, but no effect was found for the right boundary location, $F(3,45) = .613$, $p > .05$. The data are presented in Figure 2c. When all letters to the left of the fixated letter were replaced on one fixation, the duration of the next fixation was increased by 11 msec, an amount not significant. Right boundary location conditions did not differ from the control condition by more than 6 msec.

Subject Reports

In interviews following the experiment, most subjects indicated that they had been aware of the presence of errors in the text, though a few indicated no such awareness. Their impression was that the errors interfered very little with their reading, and that the errors had occurred very infrequently. At some point during the experiment, most subjects spontaneously commented about having encountered an error, and sometimes about the fact that it had seemed to go away. Interestingly,

this was usually not until they had read several passages. Most of these subjects were unaware that such errors had also occurred in earlier passages.

Discussion

Statistically significant effects of the erroneous letters were found only when the errors lay to the left of the fixated letter. However, since the goal was to identify the most distant letter replacement regions at which there was any evidence that the errors were having an effect, the trends in the data were examined visually, as well. S1 saccade length data shows a trend which suggests an effect in the Left-2 condition. However, data for the Left-4 condition is almost identical to that of the control for all variables. While no significant effects were found from errors to the right, F0 fixation duration and S1 saccade length data [illegible]h show small trends suggesting an effect at the Right-6 condition. The Right-8 condition is almost identical to that of the control. Furthermore, a visual comparison of the frequency distributions of the individual fixation durations and saccade lengths from Right-8 and Right-80 conditions indicated that they were very similar, with no suggestion of more frequent values in the higher regions for the Right-8 condition. Thus, there was no evidence that erroneous letters lying as much as four character positions to the left of the fixated letter and eight to the right were having any effect on reading. This, then, sets outer limits on the region within which distinctions among letters seem to be used by adults as they carefully

read newspaper articles. These results confirm the asymmetri character of the perceptual span as found by others (McConkie & Rayner, 1976; Pollatsek, Bolozky, Well, & Rayner, 1981).

The results of the present study were compared with those of earlier studies in order to determine whether having the letter replacement occur infrequently reveals a larger perceptual span. These comparisons indicate that the present study found effects within a narrower visual region, rather than larger region. When effects occurred, they tended to be smaller than those found in earlier studies. Rayner, Well, and Pollatsek (1980) found increments in fixations duration for conditions equivalent to our Left-2 and Left-4 conditions to range from 7 to 26 msec as compared to the present findings of slightly shorter fixations (i.e., 4 msec maximum). At Left-0 and Left-1 conditions, they found increments of 32 to 50 msec, much larger than the 26 msec difference obtained in the present study. Rayner, Inhoff, Morrison, Slowiaczek, and Bertera (1981) report that the Left-2 condition shortened forward S1 saccade lengths by .3 to .5 character positions, as compared to our .3 character position difference, while their Left-0 condition shortened saccades by 1.1 character positions, as compared to our .4. These studies generally agree that letter replacement to the right of the fixated letter has little effect on fixation durations beyond the Right-4 condition. Rayner, Inhoff, Morrison, Slowiaczek, and Bertera (1981) report no effect at Right-4 or beyond and Rayner, Well, and Pollatsek (1980) found an increase of 15 msec for the Right-4 condition. Much larger effects are seen in the

saccade lengths, with the Right-6 condition shortening saccades by 1.4 character positions, and with shortened saccades resulting from conditions up to Right 14. Rayner, Well, Pollatsek, and Bertera (1982) found forward saccades to be shortened by .8 character position in the Left-9 condition and .4 in the Left-15, as compared to our .1 at Left-8 and 0 at Left-10. These researchers concluded that letter information is taken from letters at least nine to the right, but not fifteen. (However, it should be noted that these were the only two conditions studied in this region.) McConkie and Rayner (1975) reported larger effects than these, over a still larger area. This finding was undoubtedly due to the fact, as noted in the 1975 paper, that the display changes were taking place considerably later in the fixation than was the case for the present study.

It is necessary to consider why the present study found a smaller perceptual span than those reported in the recent Rayner studies. We believe that these differences are attributable to the nature of the alternative stimuli used in the letter replacement region. In the present study, letters were replaced by other letters; in the Rayner studies, letters were replace by a square-wave grating or a pattern of X's. This may have produced different results for either of two reasons. First, it may be that, while adults tend to use letter information from the region indicated in the present study, they use other text information such as word length patterns (Rayner, 1978) or word shape information (Haber, Haber, & Furlin, 1983) from a broader region. Since a square wave grating or a pattern of X's would interfere

with the use of some of these other cues, this should lead to an indication of a larger perceptual span. The second possibility is that the critical factor in producing the difference between studies is whether or not the region containing inappropriate visual information is perceptually obvious or not. In the present study, there was no simple stimulus pattern indicating the presence of inappropriate information, whereas the presence of a square wave grating or X's in text is visually apparent even some distance into the periphery. Thus, the presence of such a pattern may be disruptive to normal reading for reasons other than the removal of normal textual information.

Thus, while the present study appears to yield a relatively clear indication of the region within which adults use letter information as they carefully read newspaper articles. the interpretation of studies using a square wave grating for letter replacement is not presently clear. Rayner (Rayner, Well, Pollatsek, & Bertera, 1982), did conduct studies in which letters were replaced by other letters, but unfortunately no control condition was included. Further studies of the type represented here are needed in order to carry out a more analytic investigation of the visual regions from which information of different types are acquired, and of the nature of the effects that result when these aspects of the stimulus pattern are removed or distorted.

Finally, the present study provides additional evidence that processing of the text occurs sufficiently fast during a fixation that the duration of that fixation and the length of the following saccade

can be influenced by information acquired on that fixation (Rayner & Pollatsek, 1981; Rayner, 1975). It also indicates that there can be lagged effects on the following fixation, as well. Thus, increased fixation durations occurring in studies in which inappropriate stimuli are present on every fixation are probably a result both of response to the stimulus present on the present fixation, and lingering effects from the prior fixation and perhaps even fixations prior to that. The same is probably also true for effects on saccade lengths.

In conclusion, the present study found no evidence to suggest that previous estimates of the perceptual span (i.e., considering this to be the region within which letter distinctions are made in reading) had been underestimated by studies in which letter replacement was occurring on every fixation. In fact, those studies appear to have provided an overestimate, due to effects which are probably specific to the nature of the stimulus pattern used to replace the letters. The present study indicates no effects from replacing letters with other letters as near at four character positions to the left of the fixated letter, and eight to the right. Effects when letters more than two to the left and six to the right were replaced were surprisingly small and not statistically significant. Thus, the size of the region within which letter distinctions are made during reading appears to be even smaller than that indicated in previous research.

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Footnote

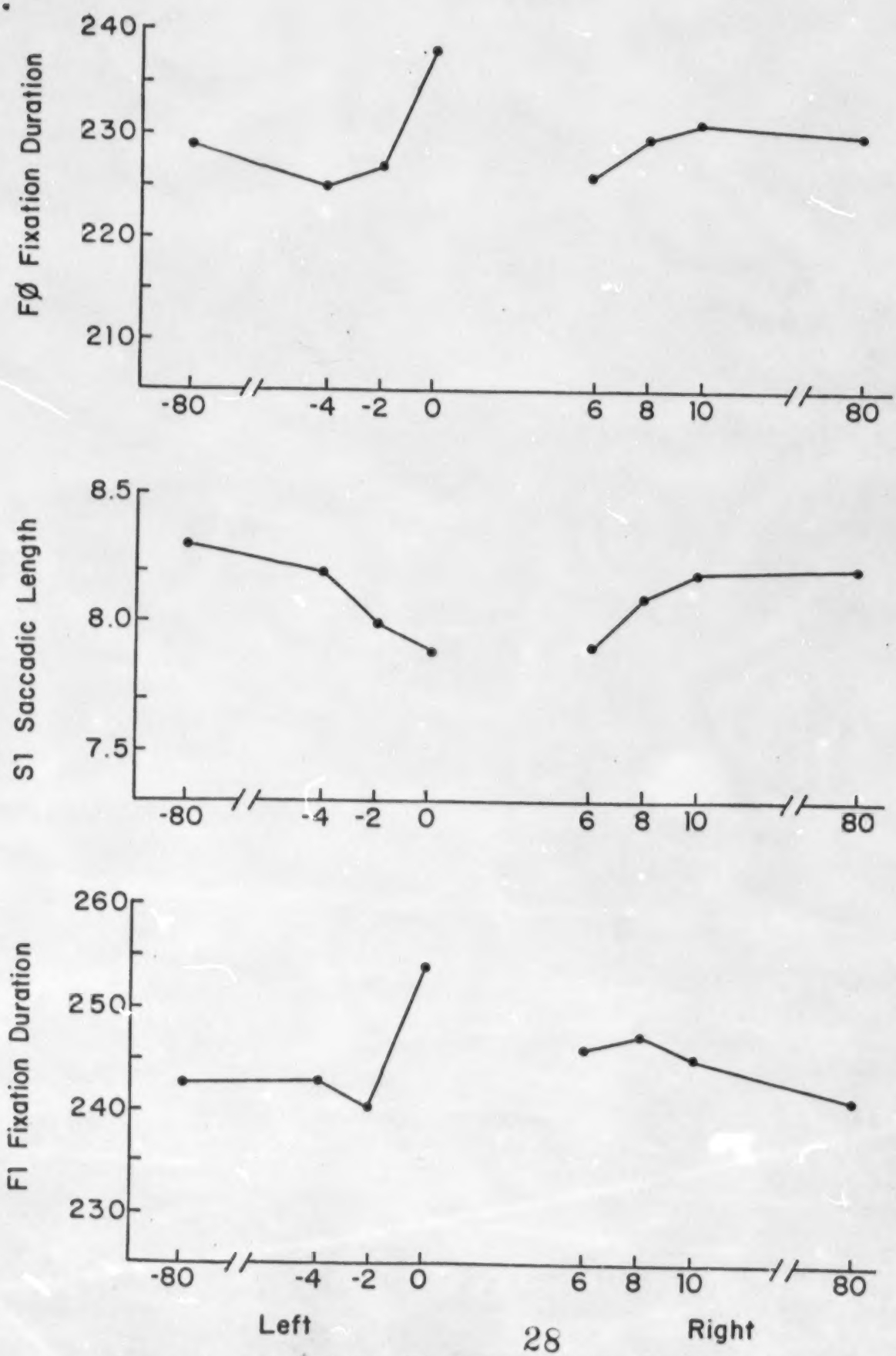
1. Throughout this paper we will speak of the character position on which the eye movement system indicates that the eyes are centered during a fixation as the "directly fixated letter." This is not meant to suggest that this particular letter is specifically being attended, or that this letter is being more directly perceived than are other nearby letters. This is simply a convenient way of describing the rotational position of the eyes. To say that a letter is the directly fixated letter indicates that the rotational position of the eyes during that fixation is approximately the same as it would be if the subject were asked to look directly at that letter position.

Figure Captions

Figure 1. Example of the appearance of part of one line of text under five different experimental conditions during a fixation on which the letter replacement occurred. During the fixation, the eyes were centered directly on the letter i in the word lighted.

Figure 2. Average time durations of fixations in msec and lengths of forward saccades in number of character positions when the letter replacement region was at different locations. F0 is the fixation on which the erroneous letters were present, F1 is the following fixation, and S1 is the saccade between them.

Condition	Appearance of the Line of Text
80 - 80	The cakes were round and lighted with candles
80 - 8	The cakes were round and lighted wbhf vmetknr
2 - 80	Xfn vmdnr xnsn souet met lighted with candles
4 - 10	Xfn vmdnr xnsn suoet mnd lighted witf vmetknr
0 - 6	Xfn vmdnr xnsn suoet met kighted xbhf vmetknr


FØ Fixation Duration
240
230
220
210
-80
-4
-2
0
6
8
10
80
S1 Saccadic Length
8.5
8.0
7.5
-80
-4
-2
0
6
8
10
80
F1 Fixation Duration
260
250
240
230
-80
-4
-2
0
6
8
10
80
Left
Right
Letter Replacement Boundary